Low-velocity impact analysis of composite plates with a buffer-zone interface between micro- and macro-modeling

C.A. Buizer

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Supervisors:
Prof. S.J. Kim
J.J. Moon
Prof. Dr. Ir. M.G.D. Geers

Seoul National University
Department of Mechanical and Aerospace Engineering
Aerospace Structures Laboratory

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Abstract

A low-velocity impact analysis on a cross-ply laminate composite is performed with a multi-scale approach. Here, multi-scale means the combined usage of micro- and macro-modeling for numerical impact simulations. To investigate failure mechanisms in composites at microscopic level, such as delamination, matrix cracking and fiber breakage, Direct Numerical Simulation (DNS) is applied. This DNS is a numerical approach based on full microscopic modeling of a structure and is solely applied on the region of interest. For the area outside the region of interest, modeling is done with a macroscopic approach based on homogenization. In order to connect both the fine meshed DNS part and the coarse meshed homogenized part, a buffer-zone interface is introduced. This buffer-zone gradually changes its mesh density from one side to the other, creating a smooth transition between the micro- and macroscopic part. In addition to that, the elements of the buffer-zone fit perfectly on its surrounding elements.

Transverse low-velocity impact simulations were performed with composite plates modeled with a full macro-scale and a multi-scale approach in order to show the added value of the micro-scale modeling. Besides, the area size in which micro-scale modeling is applied is varied to investigate its effect on local and global mechanical response and damage areas. LS-DYNA3D explicit solver is used to perform the low-velocity impact simulations on cross-ply laminate composite structures.
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Chapter 1

Introduction

Nowadays, cross-ply laminate composites are widely used in aerospace engineering applications because of their high specific strength-to-weight-ratio, their high stiffness-to-weight-ratio and their high fatigue-strength-to-weight-ratio. However, the downside of these cross-ply laminates are their vulnerability for impact damage. There are numerous situations in which impact damage can occur, for example in the situation of tool drop during maintenance or bird strike in flight. Commonly, the impact damage, such as matrix cracking, delamination and fiber fracture, is hard to indentify because it is located inside the composite material, which makes it invisible to the naked eye. The failure mechanisms mentioned cause a serious effect on the performance and safety of composite structures. Therefore, multiple non-destructive methods have been proposed in order to monitor and understand the impact damage initiation and propagation. Experimental examples of such damage monitoring methods are the lamb wave test [16] and the x-ray test [8].

Numerical approached have also been used to monitor impact damage on laminate composites. In many cases, a simulation is performed in which a spherical impactor hits a composite plate in transverse direction with a low velocity. Damage modeling is done by using failure criteria for every single failure mode. These failure criteria can roughly be distinguished into three groups: failure criteria based on damage mechanics, strength-based failure criteria and failure criteria based on fracture mechanics. Zhang et. al [20] modeled damage with failure criteria based on damage mechanics. For example, any neighboring layers where possible delaminations could occur were tied together with a 'sliding' contact interface with a damage model. Choi and Chang [3] reported a strength-based failure criteria in order to model failure modes. Therefore, a double-stress-based failure criteria was used. These criteria were founded on experimental results to study the interaction between matrix-cracking and delamination in graphite/epoxy laminated composites resulting from impact. Zheng and Sun [21] modeled damage by using failure criteria that were based on fracture mechanics. A double Mindlin type plate was proposed to predict delamination due to a low-velocity impact, by using a modified virtual crack closure method.

In all these three cases the composite structures were modeled as a stack of homogeneous orthotropic layers. In the current study, this type of modeling is referred to as macroscale modeling. In reality, each layer of the structure consist of fibers oriented in a certain direction surrounded by matrix material. A simplified representation of the composite structure is modeled when macroscale modeling is applied. A relatively low amount of elements is needed to make the mesh for these simplified models, so it is relatively cheap to compute. However, microscopic information is lost. For example, the influence of an individual fiber on the mechanical behavior is not computed. Damage that solely occurs in an individual fiber or in the matrix material can also not be monitored.

In order to prevent microscopic information to be lost, a new modeling method is proposed. This new method is based on multi-scale modeling, where multi-scale means the combined usage of micro- and macro-mechanics. Usually, impact damage occur near the place of impact. Direct Numerical Simulation (DNS) is applied in order to investigate the micro-mechanical behavior in...
this region of interest. DNS means that a structure is modeled in full microscopic detail. An
large amount of elements is needed to model a structure in full detail, so the mesh density in the
‘DNS-area’ is relatively high. Macro-scale modeling is applied for the area outside the region of
interest. Here, macroscale modeling is also the representation of a composite plate as a stack of
homogeneous orthotropic layers. The mesh density in this homogenized area is relatively low. In
order to combine the DNS-part and the homogenized part a buffer-zone interface is introduced.
This buffer-zone gradually changes in mesh density in order to connect the fine meshed DNS-part
and the coarse-meshed homogenized part. The elements of this interface fit perfectly on its sur-
rounding elements, creating a smooth transition. Overall, this multi-scale approach is a relatively
expensive method to compute.

In the first part of this report a brief explanation on DNS is given. The concept and the usage of it are discussed in more detail. In order to evaluate the multi-scale approach, transverse low-velocity impact simulations are performed. Therefore, a problem case is developed. The details about this problem case are shown in the ‘Model and impact characterization’-part. Subsequently, some information on impact induced damage modeling is given. Besides, the contact condition as it was used in the simulations is discussed. In order to show the probability of the obtained results, a comparison is made with results gained from experimental work reported in the literature. A comparison is made between a simulation performed with a fully macroscopically modeled structure and simulations performed with multi-scale models. The influence of the microscopical modeling on both global and local response is shown, as well as the influence on the monitoring of the damage area. In this study, the size of the area that is modeled in full microscopic detail in varied. The size effect of the DNS-area is also discussed. Finally, concluding remarks are made and recommendations to improve the study on this topic are given.
Chapter 2

Direct Numerical Simulation

Both microscopic and macroscopic stress and strain should be investigated in order to fully understand the mechanical behavior of composite materials and structures. Simulations performed with a macro-mechanical model presume material to be homogeneous. Besides, the effect of constituent materials are implemented solely as averaged properties of the composite. On the other hand, simulations performed with a micro-mechanical model predict the interaction of the constituents in detail. Using DNS, the stress and strain on both macroscopic and microscopic level can be determined. DNS models can be used in several applications, for example to determine the averaged elastic properties of a structure or the monitoring of impact induced damage [19]. In this study, only the monitoring of impact induced damage is performed, whereas DNS-modeling combined with macroscopic modeling is applied.

2.1 Concept

The principle of DNS is based on the simple assumption that a whole structure is discretized directly through separate modeling of constituents at the microscopic level [15] [16]. In the case of composite materials, individual fibers and matrix material are modeled in full microscopic detail. This is represented by Fig. 2.1. Furthermore, since there is no artificial assumption of the displacement or stress through the thickness, DNS can obtain directly distribution of interlaminar stress without the specific assumption as long they have enough finite discretization through the thickness. DNS-modeling can also consider the effect of inhomogeneous effect by simple direct manipulation of material properties at the level of constituents.

Figure 2.1: Basic idea of DNS on composite materials [15]
2.2 Utilize DNS

To monitor the impact induced damage of a composite plate with virtual experiments including DNS, conventional computer resources (such as a standard Personal Computer) are not sufficient, due to the relatively large amount of degrees of freedom. High computational power is required to perform simulations based on microscale modeling. Besides, the data storage require high performance computational resources. Parallel computing is proposed in order to perform numerical experiments in an efficient and effective way. In comparison to macroscale modeling, the need for high performance computational resources is the downside of the (partially) microscale modeling.

The processing part of the numerical modeling is performed with the LS-DYNA3D finite element lagrangian explicit commercial code, dedicated to analyze dynamic problems associated with large deformations, such as high velocity impact, ballistic penetration, material degradation or failure, wave propagation etc. [5]. The integration scheme is based on the central difference method and displacements and velocities are updated accordingly. The principal limitation during integration is the size of the time step, which should small enough so that a second wave cannot travel across the smallest element during one integration step. This solver program is used in a parallel computing environment using the Pegasus cluster system which consist of 400 Intel Xeon 2.2/2.4/2.8 GHZ processors [9]. Pre- and post-processing can be done in a non-parallel environment. Therefore, other software than LS-DYNA3D should be used since it only a processing program. Midas and LS-prepost can be used for the pre-processing, whereas LS-prepost can also be used for post-processing. Also Matlab was used for the post-processing of damage.
Chapter 3

Model and impact characterization

The downside of (partially) microscale modeling is that it is relatively expensive to compute. However, damage initiated on the level of constituents, like matrix cracking or fiber breakage can be monitored. To present the added value of microscale modeling, simulations are performed in which an impactor hits a composite plate in transverse direction with a low velocity. These numerical experiments were performed using a macroscale approach and the newly proposed concept with a multiscale approach.

3.1 Problem description

A problem case is developed to show the difference between impact analysis based on macroscale modeling and multi-scale modeling. In this case, a spherical impactor which is 7 mm in diameter hits a composite plate with a velocity of 10 m/s. The mass of the impactor is 0.01 kg, resulting in a impact energy of 0.5 J according to equation 3.1. The impactor is assumed to be rigid and gravitational influences are not taken into account in this research.

\[ E_i = \frac{1}{2} m_i v_i^2 \]  

(3.1)

The 200 × 200 × 1.8 mm composite plate consist of 6 layers which are stacked in a sequence of \([90^\circ/0^\circ/90^\circ]_2\). There are two interfaces in which the direction of the fiber changes. The model contains boron as a fiber material and epoxy as matrix material. The volume-fraction of the fiber \(V_f = 0.47\). The edges of the composite plate are assumed to be clamped, which means that they are fixed in the numerical experiments. A representation of the problem situation is presented in Fig.3.1

Figure 3.1: Representation of the transverse low-velocity impact problem
The mechanical properties of the boron, epoxy and homogenized material can be found in Table 3.1. The homogenization of the material is based on the mechanical response of a unit cell as depicted in Fig. 3.2. This unit cell with a similar mesh was used by Ji in a DNS-model in order to determine the homogenized mechanical properties of it. The boron and the epoxy are obviously isotropic materials, whereas the homogenized material behaves as an orthotropic material, due to fiber orientation.

![Unit cell model of a fiber/matrix combination](image1)

**Table 3.1: Material properties**

<table>
<thead>
<tr>
<th></th>
<th>$E_x$(GPa)</th>
<th>$E_y$(GPa)</th>
<th>$\nu_{xy}$</th>
<th>$\nu_{yz}$</th>
<th>$G_{xy}$(GPa)</th>
<th>$G_{yz}$(GPa)</th>
<th>$\rho$(g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boron</td>
<td>420</td>
<td>420</td>
<td>0.2</td>
<td>0.2</td>
<td>170</td>
<td>170</td>
<td>2.45</td>
</tr>
<tr>
<td>Epoxy</td>
<td>3.5</td>
<td>3.5</td>
<td>0.33</td>
<td>0.33</td>
<td>1.25</td>
<td>1.25</td>
<td>1.54</td>
</tr>
<tr>
<td>Homogenized</td>
<td>199.4</td>
<td>6.55</td>
<td>0.21</td>
<td>0.21</td>
<td>2.45</td>
<td>2.45</td>
<td>1.97</td>
</tr>
</tbody>
</table>

**Figure 3.2: Unit cell model of a fiber/matrix combination**

3.2 Mesh architecture

The meshing of the composite plates is totally different for the fully macroscopically modeled homogenized model than for the multi-scale model. This section shows the meshes as they were used for the numerical experiments.

3.2.1 Macroscale model

As mentioned before, structures modeled by a macro-mechanical approach are represented as a stack of homogeneous orthotropic layers. In this case, six layers are modeled separately, whereas the mechanical properties that were assigned depended on the fiber orientation of each layer. The mesh density near the impact area is higher than the mesh density in the surrounding area, because this is the region where local information is important in order to monitor impact damage. A cross-sectional cut view can be seen in Fig. 3.3

![Macroscopic modeling of the composite plate](image2)
3.2.2 Multi-scale model

Full microscopic detail of the area around the impact is modeled in the multi-scale modeling approach. Therefore, the unit cell as it is depicted in Fig. 3.2 was stacked, creating a DNS-part as it is shown in Fig. 3.4. The size of the DNS-area can be varied very easily using this stacking method. However, for more complex oriented stacking sequences such as $[0^\circ/45^\circ]_s$ this method is less suited, since it is hard to find a unit cell that can be stacked properly. The area that is not modeled in a microscopic manner, is modeled like it is done in the macroscale model. The meshes of both the fine meshed DNS-part and the coarse meshed homogenized part are connected with a buffer-zone interface (Fig. 3.5). This interface is a simple structure that consist of elements. The elements of this buffer-zone fit perfectly on top of its surrounding elements. The mesh density gradually changes, creating a smooth transition between the micro- and macroscopic modeled parts. This interface also consists of individual layers each having its own homogeneous orthotropic material property which depends on the orientation of each particular layer. No tyings were used to connect the elements of the buffer-zone to its surrounding elements.

Figure 3.4: DNS-model of a laminate composite

Figure 3.5: Buffer-zone meshing
Numerical modeling

There is a wide variety of failure modes that can occur in impact-induced damage. In order to monitor this damage in composite plates, many failure criteria have been proposed. In the introduction it was mentioned that they could be distinguished into three groups: failure criteria based on fracture mechanics, strength-based failure criteria and failure criteria based on damage mechanics. Strength-based failure criteria for each failure mode are discussed in this report. These criteria can be incorporated in material models that are usable for impact simulation with micro- or multi-scale models. The discussed failure criteria comprise the calculated stresses to their related strength parameter.

At the time the numerical experiments were done, no material models were available that include a single failure mode for each constituent (fiber, matrix and interfaces). Instead, material models that incorporate multiple failure modes which describe both failure of matrix and fiber material together exist. These can not be applied on individual constituents. Therefore, damage could not be simulated correctly because its effect on the mechanical behavior of the composite laminate is not computed. Delamination has a specific property and therefore it is simulated in order to verify the reliability of the results. Once more, the effect of the delamination on the mechanical behavior is not computed.

Another important issue in impact simulations is contact. In order to characterize the interaction between separate objects that hit each other, contact conditions need to be applied. The contact condition that is used in this study is also discussed in this section.

### 4.1 Failure characterization

Many strength-based failure criteria have been proposed. A group of these criteria describe the failure of only one single failure mode. Others describe the failure due to interactive failure modes, like the Tsai-Hill criterion [1]. One other group describes the macroscopic failure in composite plates, for example the Tsai-Wu criterion [17]. These last two groups are generally used in macro-scale models and are not sufficient for describing failure at the microscopic level. This study concerns the criteria that describe single failure modes, since that are the ones that are needed for progressive damage modeling on microscopic level. The failure modes that are discussed are: fiber breaking, fiber buckling matrix fracture, matrix compression, fiber debonding and delamination.

#### 4.1.1 Fiber breaking

Fiber breaking occurs in the fibers due to tension in the fiber direction. This failure mode can be modeled in various manners. The maximum stress form is the most simple form of the failure breaking criterion. In this criterion, fiber breakage occur when the tensile stress $\sigma_{xx}$ along the fiber direction satisfy the following equation [13]:

\[ \sigma_{xx} \leq \sigma_{f} \]
\( \sigma_{xx} \frac{1}{Y_{xx}} = 1 \ (\sigma_{xx} > 0) \) (4.1)

\( Y_{xx} \) is in this equation the tensile failure stress in the fiber direction. The local stress \( \sigma_{xx} \) drops to zero if fiber breakage occurs. A more extensive criterion is given by Hashin [6]. This more extensive criterion includes contributions of shear stresses.

### 4.1.2 Fiber buckling

Fiber buckling occurs in the fibers due to compression in the fiber direction. The failure criterion in its most simple form is similar to the fiber breakage criterion. Buckling of the fiber occurs as the following is true:

\[ \frac{\sigma_{xx}}{|Y_{xx}|} = 1 \ (\sigma_{xx} < 0) \] (4.2)

\( Y_{xx} \) is in this equation the compressive failure stress in the fiber direction. The local stiffness matrix can be modified in order to compute the change in mechanical behavior due to fiber buckling [5]. Also in this case more extensive failure criteria are available.

### 4.1.3 Matrix fracture

Matrix fracture is also referred to as matrix cracking. Cracks occur in the matrix material as a result of microscale imperfections in the fiber-matrix interface zone [12]. In order to model the matrix failure, Hashin [6] proposed a failure criterion, where matrix cracking occurs when the following equation is satisfied:

\[ \frac{1}{\sigma_T^2}(\sigma_{yy} + \sigma_{zz})^2 + \frac{1}{\tau_T^2}(\sigma_{yz}^2 - \sigma_{yy}\sigma_{zz}) + \frac{1}{\tau_A^2}(\sigma_{xy}^2 + \tau_{xz}^2) = 1 \ (\sigma_{yy} + \sigma_{zz} > 0) \] (4.3)

\( \sigma_T, \tau_T \) and \( \tau_A \) are respectively the tensile failure stress transverse to fiber direction, the transverse failure shear and the axial failure shear. This implies that for every single layer a local coordinate systems need to be used in order to model matrix mode failure, which makes it more complicated to model than fiber mode failure. In equation 4.3 it is assumed that the failure plane has a 45 degree orientation with respect to the global coordinate system. Local stress components \( \sigma_{nn}, \sigma_{nt} \) and \( \sigma_{ln} \) (Fig. 4.1) can be written as functions of global stress components and the angle of the failure plane with respect to the global coordinate system. Resulting in a more general failure criterion:

\[ f(\sigma_{nn}, \sigma_{nt}, \sigma_{ln}) = \left( \frac{\sigma_{nn}}{\sigma_T} \right)^2 + \left( \frac{\sigma_{nt}}{\tau_T} \right)^2 + \left( \frac{\sigma_{ln}}{\tau_A} \right)^2 = 1 \ (\sigma_{nn} > 0) \] (4.4)

Figure 4.1: Local stress components
4.1.4 Matrix compression

Yielding of matrix material can occur when the matrix material is in compression. To model this behavior a failure criterion is proposed in which failure occurs as the following equation is satisfied:

$$
\frac{1}{\sigma_T} \left[ \left( \frac{\sigma_T}{2\tau_T} \right)^2 - 1 \right] (\sigma_{yy} + \sigma_{zz}) + \frac{1}{4\tau_T^2} (\sigma_{yy} + \sigma_{zz})^2 + \frac{1}{\tau_T} (\sigma_{yz} - \sigma_{yy} \sigma_{zz}) + \frac{1}{\tau_A^2} (\sigma_{yy}^2 + \sigma_{zz}^2) = 1 \quad (\sigma_{yy} + \sigma_{zz} < 0)
$$

(4.5)

Also in this failure criterion it is assumed that the failure plane has a 45 degree orientation with respect to the global coordinate system.

4.1.5 Fiber debonding

Fiber debonding often occur at the tip of a crack in the matrix material. This crack can propagate inside fiber material, but it can also propagate along the fiber-matrix interface causing fiber debonding. This principle is depicted in Fig. 4.2.

Figure 4.2: Fiber penetration (left) and fiber debonding (right) induced by a crack in the matrix material [18]

Wang [18] used a strength-based fiber debonding criterion. Applying his failure criteria on the fiber/matrix interfaces, would result in fiber debonding as the following equation was satisfied:

$$
\left( \frac{\sigma'_{22}}{\sigma_t} \right) + \left( \frac{\sigma'_{12}}{\tau_s} \right) = 1
$$

(4.6)

$\sigma'_{22}$ and $\sigma'_{12}$ are local stress components. Their orientation with respect to the global coordinate system is shown in Fig. 4.3. $\sigma_t$ and $\tau_s$ are respectively the tensile and shear strength of the interface.

Figure 4.3: Local coordinate system with corresponding stress-components with respect to the global coordinate system
4.1.6 Delamination

Delamination is the act of splitting a laminate into layers. This splitting usually happens at the interface of layers with different fiber orientation. A Quadratic Delamination Criterion (QDC) is proposed by Brewer and Lagace [2] which relates the delamination to averaged interlaminar out-of-plane stresses. The mismatch in bending stiffness of individual layers has a significant contribution in the formation of these interlaminar out-of-plane stresses [4]. According to the simplified QDC developed by Brewer and Lagace, delamination should occur when the following equation is satisfied:

\[
\left( \frac{\sigma_{tzz}}{Y_{tzz}} \right)^2 + \left( \frac{\sigma_{czz}}{Y_{czz}} \right)^2 + \left( \frac{\sigma_{xz}}{Y_{xz}} \right)^2 = 1 \quad (4.7)
\]

where \( Y_{tzz}, Y_{czz} \) and \( Y_{xz} \) are respectively the out-of-plane tensile failure stress, out-of-plane compressive failure stress and the transverse failure stress. This failure criterion includes the cases in which the out-of-plane stress is in tension or in compression. Obviously, when the out-of-plane stress is positive, the compressive component \( \left( \frac{\sigma_{czz}}{Y_{czz}} \right)^2 \) should not be included. The other way around, in the case that this out-of-plane stress is negative, the tensile component \( \left( \frac{\sigma_{tzz}}{Y_{tzz}} \right)^2 \) should not be included.

As one of the distinguishing features, delamination areas are generally oblong-shaped with their major axis being coincident with the fiber orientation of the layer below the interface. For \([0°/90°]-\)interfaces, typical peanut-like shapes have been reported in the literature [11,14]. This distinguishing feature was used to verify the reliability of the results obtained by the numerical experiments preformed in this study. Instant stress values at each increment of the simulation are used to compute delamination. These stress values are exported from LS Dyna to Matlab for post-processing.

4.2 Contact condition

LS-DYNA3D offers a penalty-based contact condition, which is also used in the numerical experiments performed in this study. The interaction between the separate objects making contact is represented by linear springs. Whereas objects are discretized into segments, every segment contains its own contact stiffness. The stiffness of this linear springs can be calculated as for every segment \( i \) as follows:

\[
k_i = \frac{f_s \cdot A_i^2 \cdot K_i}{V_i} \quad (4.8)
\]

with:

\[
f_s = SLSFAC \cdot SFS \quad (4.9)
\]

\( SLSFAC \) is a scale factor on default slave penalty stiffness and \( SFS \) is a penalty scale factor.

The area \( A_i \), the bulk modulus \( K_i \) and the volume \( V_i \) that are included in 4.8 are properties of the contact segment. The contact stiffness depends on the bulk modulus, so it is material dependent. Contact stiffness is used in order to calculate contact forces.
Chapter 5

Performance

In order to predict mechanical behavior with a finite element method algorithm, assumptions and simplification need to be made. Only results which are an approximation can be obtained. Results should be verified with experimental tests in order to show the accuracy of it. In this study, no experiments have been done in order to verify the results. Therefore, a discussion on the reliability of the results can be found in the chapter. As mentioned before, the delamination area has a typical peanut-like shape at $[0^\circ/90^\circ]$-interfaces. This property makes it interesting to look at the delamination area in order to verify whether the results are reasonable.

After the evaluation of the results, a comparison is made between the results obtained by the multi-scale approach and the traditional macroscale approach. Both global and local response will be examined and compared. Besides, the influence of the size of the area that is modeled in full microscopic detail on the microscopic and the macroscopic mechanical behavior will be discussed. Multi-scale models with DNS-areas that have a size of $2.1 \times 2.1$, $4.2 \times 4.2$, $6.3 \times 6.3$, $8.4 \times 8.4$ and $10.5 \times 10.5$ mm are investigated.

5.1 Validation

Interlaminar $z_x$-stress fields and delamination areas at the upper $[90^\circ/0^\circ]$-interface of a multi-scale model ($10.5 \times 10.5$ mm) are depicted in Fig. 5.1. The inner square in each subplot is the area that is modeled in full microscopic detail. The area around the DNS-part is the buffer-zone. The blue color in the lower figures represents non-delaminated material. Every other color represents material that is delaminated. Equation 4.7 is used in order to calculate the delamination. Once more, the influence of the delamination on the mechanical behavior is not included in the calculation.

Fig. 5.1 shows that both $z_x$-stress and delamination area increases in time until 32 $\mu$s. From that time on, stresses decrease again and the delamination area does not grow further. It can be observed that the delamination area has its peanut-like shape as it is reported in the literature. Its major axis is oriented in the fiber direction of the layer underneath the interface, which is in this case in vertical direction.
The similar response can be seen in the lower [0°/90°]-interface (Fig. 5.2). The major axis of the delamination area is rotated by 90 degrees, which can be explained by the fact that the fibers of the layer underneath this interface are rotated by 90 degrees as well.

It should also be mentioned that the delamination area of this lower [0°/90°]-interface is bigger than the delamination area of the upper [90°/0°]-interface. This is caused by the difference in bending moment in each interface. This difference in bending moments causes relatively high stresses in the lower interface, which results in a relatively large delamination area. The difference in delamination area size is reported in the literature [7]. It can be concluded that reasonable damage predictions are made.

Near the edge between the DNS-part and the buffer-zone, stress concentrations can be observed. This is caused by the sudden transition of materials. Though stresses are calculated wrongly near
this interface between the DNS-area and the buffer-zone, it does not affect the shape of the delamination area. To do reasonable damage monitoring, the area that is modeled in full microscopic detail should be sufficiently large. The stress concentrations near the edge of this area should not affect the damage area.

The interaction between the impactor and the composite laminate is visualized in Fig. 5.3. The contact force is the force that interacts between the impactor and the composite plate. The contact force and the stresses (Fig. 5.4) that occur in the structure have the same global response in time, which is obvious because stresses get higher when a load increases. It can be concluded from Fig. 5.3 and Fig. 5.4 that the contact conditions are applied in a proper fashion.

![Figure 5.3: Time history of the contact force](image1)

![Figure 5.4: Time history of the zx-stress near the impact](image2)

### 5.2 Macroscale versus Multi-scale

Now it is proven that the performed simulations produce reasonable damage predictions, a comparison can be made between the macroscale approach and the multi-scale approach. This comparison will be made on both global and local level.
5.2.1 Global response

In order to compare the global response of both macroscale and multi-scale approaches, the deflection of the composite plate is investigated. The deflection of the plate at the place of impact is shown in Fig. 5.5. A clear difference between the global response of the macroscale and multi-scale models can be observed. Local differences in stiffness can be given as a reason for the discrepancy in global response. As can be seen in Fig. 5.6, the deflection of the composite plate at the edge of the buffer-zone interface is also different between the macro- and multi-scale models. This implies that the difference in local stiffness is not the only cause of the contrast in global response.

![Figure 5.5: Time history of the deflection of the composite laminate at the place of impact](image)

As mentioned in chapter 4.2, contact stiffness is dependent on the contact material. Whereas the impactor of the macroscale simulations contact homogenized material, the impactor of the multi-scale simulations contacts epoxy. This causes a difference in contact stiffness between both approaches, resulting in a dissimilarity in contact forces. As it was observed in the previous section, the stresses are heavily influenced by the amount of contact force. So the contrast in contact materials lead to a difference in contact force, stress fields and thus the global response.

![Figure 5.6: Time history of the deflection of the composite laminate near the edge of the buffer-zone interface](image)
Individual multi-scale models with different DNS-area sizes show a negligible variation. The global response is hardly influenced by the size of the DNS-area.

5.2.2 Local response

The size of the DNS-area does not have an effect on the global response of the composite plate, but it does have an effect on the local mechanical response. As mentioned before, stress concentrations can be observed at the interface between the DNS-area and the buffer-zone. These stress concentrations may have an effect on the damage monitoring. This is visualized in Fig. 5.7. The stress concentrations of the 4.2 × 4.2 mm multi-scale simulation affect the shape of the damage area at the edge between the DNS-part and the buffer-zone. Therefore, the DNS-area should be sufficiently large. A DNS area of 8.4 × 8.4 mm is in this case sufficient in order to monitor delamination properly.

Figure 5.7: $\sigma_{zx}$-stress and delamination of multiple models at the lower [0°/90°]-interface at $t = 32\mu s$

The difference in local response between the macroscale and multi-scale simulations is enormous. No delamination was predicted in the macroscale simulations, which is in total contrast with the delamination area predicted by the multi-scale simulations. The multi-scale results present a distinct difference for the spatial $\sigma_{zx}$-stress distribution across the lower [0°/90°]-interface as compared to the macroscale results. Unlike the macroscale stress, the distribution of the multi-scale stress is clearly non-uniform. As can be observed, the effect of the fiber and matrix are definitely distinguished in the multi-scale results, while they are absent in the macroscale results.

Stress concentrations occur at fiber-matrix interfaces, because of the sudden transition in material. These stress concentrations can be observed in the multi-scale results, but not in the macroscale results. The stress concentrations contribute in the difference in the magnitude of stresses between both methods. The difference in contact material is another reason for different magnitudes of stress. The magnitude of stress in the multi-scale models is higher than the magnitude of stress in macroscale models, so a larger damage area will be monitored by the multi-scale approach.

Also the stress gradients are higher in the multi-scale simulations. Steep stress gradients are shown in the interfaces where fiber angles are changed. This effect can not be observed in the macroscale simulation, since the layer micro-structure is smeared (Fig. 5.8). It can be concluded
that the multi-scale modeling has an advantage for describing the local stresses in the region of interest in comparison to macroscale modeling.

Figure 5.8: Through-the-thickness variation of the Von Mises-stress at $t = 32 \mu s$
Chapter 6

Conclusions and Recommendations

In order to monitor impact-induced damage, numerical experiments were performed in which an impactor hits a composite plate in transverse direction with a low velocity. The composite plate was modeled by a traditional macroscopic approach and a new proposed multi-scale approach. The multi-scape models consisted of a microscale part and a macroscale part connected by a buffer-zone interface. Full microscopic detail was modeled in the microscale part. Although the multi-scale simulations are relatively expensive to compute, microscopic information is not lost.

Failure models for a wide variety of failure modes were available, but not yet individually incorporated in finite element programs. A progressive model to predict delamination was used in order to monitor delamination, although the influence of the delamination on the mechanical behavior was not computed.

The results of the simulations were verified, with experimental results reported in literature. Reasonable damage monitoring was done. Local stresses were calculated wrongly near the edge between the micro-scale part and the buffer-zone, because of material mismatch. These wrongly calculated stresses do not have any influence on the damage area in case the area which is modeled in full microscopic detail is sufficiently large.

By comparing the macroscale and multi-scale results, it could be concluded that microscale modeling has a significant influence on both global and local response. On the one hand these differences were caused by local geometrical and material property differences. On the other hand it was caused by the contrast in contact stiffness. Contact forces were different in magnitude, resulting in different magnitudes of stress.

6.1 Recommendations

Not all damage models for each failure mode were included in the simulations, so in order to improve the numerical experiments, material models which include failure modes models for every single constituent (fiber, matrix and interfaces) should be included. Besides, their influence on the mechanical behavior should be computed. Failure criteria as they were given in chapter 4.1 can be used for these kind of material models

Simulations with a relatively low impact energy were performed in this study, causing a large difference in the response of the macro-scale and the multi-scale simulations. This difference may be reduced or increased when a larger impact load is applied. Research on this topic should be done.
Local stress concentrations near the edge between the DNS-part and the buffer-zone can be minimized by using a high mesh density.

Even though the obtained results seem reasonable, they should be verified by experimental tests.
References


